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אני, (שם המבקש, מען ולגבי גוף מאוגד - מקום התאגדותו)  
(Name and address of applicant, and in case of body corporate-place of incorporation)

ידע חברת מחקר ופיתוח בע"מ, חברה ישראלית, ליד מכון ויצמן למדע, ת.ד. 95, רחובות 76100  
Yeda Research and Development Co. Ltd., Israeli Company, at the Weizmann Institute of Science,  
P.O.Box 95, Rehovot 76100

ממצאים: גרי הודה, יצחק מסתאי, משה הומיאונפר ורשף טנא  
Inventors: Gary Hodes, Yitzhak Mastai, Moshe Homyonfer and Reshef Tenne

בعل אמרצתה מכת Assignment  
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(בעברית)  
(Hebrew)

Synthesis of inorganic fullerene-like nanoparticles of metal chalcogenides

(באנגלית)  
(English)

hereby apply for a patent to be granted to me in respect thereof.

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**SYNTHESIS OF INORGANIC FULLERENE-LIKE NANOPARTICLES  
OF METAL CHALCOGENIDES**

**סינטזה של ננו-חלקיים אי-אורגניים דמווי פולרנים של שלקוגנידים של מתכות**

**Yeda Research and Development Co. Ltd.**

Inventors: Gary Hodes, Yitzhak Mastai,  
Moshe Homyonfer, Reshef Tenne

**ידע חברת מחקר ופיתוח בע"מ**

**ממציאים : גרי הודה, יצחק מסתאי,  
משה הומיוונפר, רשף טנה**

## FIELD AND BACKGROUND OF THE INVENTION

The present invention relates in general to a method for preparing inorganic fullerene-like structures of metal, e.g. transition metal, chalcogenides, particularly, to sonoelectrochemical synthesis of such inorganic fullerene-like structures, and more particularly to room temperature sonoelectrochemical synthesis of molybdenum sulphide.

Since the discovery of the original fullerenes, C<sub>60</sub> and C<sub>70</sub><sup>[1]</sup> and, retrospectively, multi-shell closed carbon structures<sup>[2]</sup>, a wide range of related fullerene-like structures have been identified. These include closed structures of other materials such as WS<sub>2</sub><sup>[3]</sup>, MoS<sub>2</sub><sup>[4]</sup>, NiCl<sub>2</sub><sup>[5]</sup> and other shapes, in particular nanotubes, of many of the above materials<sup>[1,3,5,6]</sup> as well as of BN<sup>[7]</sup> and VO<sub>x</sub>.<sup>[8]</sup> All these closed structures require high temperatures for their formation to provide the high energy needed for their closure. Methods used to provide these temperatures include, besides the arc discharge technique commonly used for carbon fullerenes<sup>[9]</sup>, laser vaporization<sup>[1]</sup> and heating in a furnace.<sup>[3,4]</sup> Other techniques, based on local heating, include electron<sup>[10]</sup> and ion beam<sup>[11]</sup> treatment and high electric current densities from an STM tip.<sup>[12]</sup> Room temperature crystallization of amorphous WS<sub>3</sub> into closed structures of WS<sub>2</sub> has been reported to occur over several years<sup>[10]</sup>, demonstrating the thermodynamic stability of these structures, but illustrating the large kinetic barriers for their formation.

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Particles of inorganic structures having a layered configuration (a single layer or nested layers) are known as inorganic fullerenes (IF). For ease of discussion, inorganic layered structures such as, but not limited to, spheres, whiskers, nanotubes, polyhedral and others, will interchangeably be referred to as "inorganic fullerene-like" or "IF" materials, throughout the specification.

Nanoclusters of IF metal chalcogenide materials, such as WS<sub>2</sub> and MoS<sub>2</sub>, were recently described (Refs. 3 and 10 herein and EP 0 580 019). Thus, according to European Patent No. 0 580 019 of the same applicants, a method was described

for the preparation of oriented thin films of the transition metal chalcogenides WS<sub>2</sub>, WSe<sub>2</sub>, MoS<sub>2</sub> and MoSe<sub>2</sub> from the corresponding metal oxides, whereby in some conditions the nanoclusters of the layered IF metal chalcogenide materials were shown to be unstable against folding and to close upon themselves to form nested IF nanoparticles such as nested fullerene-like structures and nanotubes. These conditions could not be controlled and thus the method according to the above-mentioned publications do not allow to obtain high yields of macroscopic quantities of the IF metal chalcogenide, nor to determine the size and shape of the particles.

A gas phase synthesis for the preparation of a few milligrams of IF-MoS<sub>2</sub> from a molybdenum trioxide precursor and H<sub>2</sub>S in a reducing atmosphere has been described, [4] taking advantage of the sublimation of the molybdenum suboxide (MoO<sub>3-x</sub>) under reducing conditions above 700 °C. Thus, a portion of 30 mg of MoO<sub>3</sub> powder (>99% pure) was heated (>800 °C) and slowly reduced to MoO<sub>3-x</sub> by a stream of forming gas (typically 5%H<sub>2</sub>/95%N<sub>2</sub>). The suboxide (MoO<sub>3-x</sub>) sublimed and effused out of a nozzle where it crossed a stream of H<sub>2</sub>S gas mixed with a forming gas. After some 3-5 minutes, the entire load (30 mg) of MoO<sub>3</sub> sublimed, the reaction products were collected on a quartz substrate, positioned few cm away from the crossing point of the two gas streams and maintained at the same temperature (>800 °C), and the collected nanoparticles were progressively converted into nested layer polyhedra within ca. 30 minutes of firing time. The average size of the oxide particles and the ensuing IF-MoS<sub>2</sub> particles increased with temperature. It was found that above 900 °C, platelets with 2H-MoS<sub>2</sub> structure abound, and became the sole product above 950 °C. According to the above-described gas phase reaction it is difficult to obtain very high quantities of the IF structures of transition metal chalcogenides. The IF particles have several interesting and useful applications, and it would be very advantageous to have a method and apparatus for high yield preparation of macroscopic quantities of IF particles of metal, e.g. transition metal, chalcogenides.

The use of ultrasonic radiation to increase the rate of chemical reactions is well known and related to the phenomenon of cavitation, whereby very high local temperatures and pressures are transiently formed (sub- $\mu$ s) in collapsing bubbles.<sup>[13]</sup> More recently, the combination of sonochemistry and electrochemistry (sonochemical electrochemistry) has been investigated. Among the characteristics of this technique are acceleration of mass transport, cleaning and degassing of the electrode surface and increased reaction rates.<sup>[14]</sup> Sonochemical electrochemical formation of nanoscale metal powders<sup>[15]</sup> has been accomplished by applying an electric current pulse to nucleate the electrodeposit, followed by a burst of ultrasonic energy which removes the metal particles from the sonic probe cathode.

#### SUMMARY OF THE INVENTION

Based on the assumption that the short bursts of local high temperature may allow formation of closed structures at nominal room temperature, we used the known process for cathodic electrodeposition of MoS<sub>2</sub> from solutions of thiomolybdate ions.<sup>[16,17]</sup> The MoS<sub>2</sub> deposited using this technique is normally amorphous as deposited and becomes crystalline after heat treatment forming a highly-textured film.<sup>[17]</sup> This high degree of texture suggests a planar structure.

Using the same basic technique, but depositing onto an ultrasonic probe using the principle described above of a current pulse followed by an ultrasonic pulse to remove the deposit from the probe/electrode, it was found that a black deposit of molybdenum sulphide formed in the solution.

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It should be noted that the term "inorganic fullerene-like" ("IF"), as used herein in the specification and claims, refers to inorganic metal chalcogenide structures having one layer or nested layers which form what is known in the art as a closed cage<sup>[3]</sup> which may encage a void (i.e., be hollowed) or a core or may form a stuffed nested layer structure, i.e. a structure containing a material other than the metal material precursor encaged within nested layers of the metal chalcogenide. In particular the term refers to structures such as what is known in the art as single and double layer inorganic fullerenes, nested layers inorganic fullerenes, stuffed

inorganic fullerenes, single layer nanotubes, nested nanotubes, stuffed nanotubes, and inorganic superlattice structures, i.e. IF particles having layers of two or more different chalcogenides of the metal, e.g.  $WS_2$  and  $WSe_2$ .

According to the method of the present invention, IF nanoparticles of metal chalcogenides including one or more layers of desired sizes and shapes, e.g., spheres, sphere-like, nanotubes and polyhedral shapes, may be manufactured.

The metals that are suitable for this method are metals that form layered metal chalcogenide products such as In, Ga, Sn and a transition metal selected from Mo, W, V, Zr, Hf, Pt, Re, Nb, Ta, Ti, Cr and Ru.

The present invention thus relates to a method for the sonoelectrochemical liquid phase synthesis of inorganic fullerene-like (hereinafter IF) structures of metal chalcogenides, wherein said metal is selected from In, Ga, Sn and a transition metal selected from Mo, W, V, Zr, Hf, Pt, Re, Nb, Ta, Ti, Cr and Ru, and the chalcogen is S, Se or Te, the method comprising the steps of:

- (a) dissolving in a suitable solvent: (a) at least one compound of said metal and at least one compound of said chalcogen, or (b) at least one said chalcogen-containing said metal compound;
- (b) immersing an electrically conductive ultrasonic probe in the solution obtained in (a);
- (c) electrically connecting the ultrasonic probe, which operates as an electrode, to one terminal of an electric power supply, and the other terminal of said electric power supply is connected to a counter electrode;
- (d) applying an ultrasonic signal to said ultrasonic probe electrode and an electric voltage to both the ultrasonic probe electrode and the counter electrode; and
- (e) recovering the IF metal chalcogenide structures that precipitated in (d).

The solvent in step (a) may be aqueous or non-aqueous. Examples of non-aqueous solvents are, but not limited to, alcohols and dimethyl sulfoxide (DMSO). The synthesis is carried out at a temperature in which said solvent is in

the liquid state. For example, when the solvent is water, the synthesis may be carried out at room temperature.

The ultrasonic probe is preferably a Ti probe. In a preferred embodiment, in step (d), first an electric voltage is applied to both the ultrasonic probe electrode and the counter electrode and is then followed by an ultrasonic signal to the ultrasonic probe electrode, and the sequences of electric voltage and ultrasonic signal are repeated until the desired amount of IF-metal chalcogenide structures is obtained.

In another preferred embodiment, the ultrasonic probe electrode is connected to the negative terminal of the electric power supply and the counter electrode is connected to the positive terminal.

As described above, the metals that are suitable for this method are metals that form layered metal chalcogenide products. Examples of metal chalcogenides that form layered products and are suitable for the preparation of IF structures according to the method of the invention include, but are not limited to,  $WS_2$ ,  $WSe_2$ ,  $MoS_2$ ,  $MoSe_2$ ,  $SnS_2$ ,  $SnSe_2$ ,  $RuS_2$ ,  $GaS$ ,  $GaSe$ ,  $In_2S_3$ ,  $In_2Se_3$ ,  $InS$ ,  $InSe$ , etc. [for additional examples, see A. F. Wells, Structural Inorganic Chemistry, 5th edition, Oxford Science Publications (1993); Chemistry of the Elements, by N. N. Greenwood and A. Earnshaw, Pergamon Pres, Oxford (1990)].

The metal compound according to the invention may be an oxide that is soluble in an electrolyte, for example  $MoO_3$  and  $WO_3$ , that are soluble in alkaline solutions.

The chalcogen according to the invention is S, Se or Te, and the chalcogen compound may be a chalcogen, a compound containing a chalcogen, a mixture of chalcogens, a mixture of compounds containing a chalcogen and a mixture of a chalcogen and a compound containing a chalcogen. The chalcogen material is preferably a chalcogen compound such as  $H_2S$ ,  $H_2Se$ , and/or  $H_2Te$ ,  $Na_2S$ ,  $Na_2Se$ , and/or  $Na_2Te$ , and  $CS_2$ .

The size of the IF particles produced by the method of the invention is in the nanometer range, typically some tens of nanometers and also hundreds of nanometers. Nanotubes may be even longer.

The IF structures produced by the method of the invention include, but are not limited to, single layer inorganic fullerenes, nested layers inorganic fullerenes, stuffed inorganic fullerenes, single layer nanotubes, nested nanotubes, stuffed nanotubes, inorganic superlattice structures, and structures with negative curvature (Schwartzites).

In a preferred embodiment, the metal is a transition metal selected from Mo, W, V, Zr, Hf, Pt, Re, Nb, Ta, Ti, Cr and Ru, more preferably it is Mo.

In a preferred embodiment, the invention relates to a method for the sonoelectrochemical synthesis of inorganic fullerene-like (hereinafter IF) structures of molybdenum sulphide, comprising the steps of:

- (a) dissolving in a suitable solvent at least one molybdenum compound and at least one sulphur compound or a sulphur-containing molybdenum compound;
- (b) immersing an electrically conductive ultrasonic probe in the solution obtained in (a);
- (c) electrically connecting the ultrasonic probe, which operates as an electrode, to one terminal of an electric power supply, and the other terminal of said electric power supply is connected to a counter electrode;
- (d) applying an ultrasonic signal to said ultrasonic probe electrode and an electric voltage to both the ultrasonic probe electrode and the counter electrode; and
- (e) recovering the molybdenum sulphide IF structures that precipitated in (d).

In a most preferred embodiment, the method for sonoelectrochemical liquid phase synthesis of IF-like structures of molybdenum sulphide is carried out at room temperature, comprising the steps of:

- (a) dissolving ammonium tetrathiomolybdate in water;

- (b) immersing an electrically conductive ultrasonic Ti probe in the solution obtained in (a);
- (c) electrically connecting the ultrasonic probe, which operates as an electrode, to one terminal of an electric power supply, and the other terminal of said electric power supply is connected to a counter electrode;
- (d) applying an ultrasonic signal to said ultrasonic probe electrode and an electric voltage to both the ultrasonic probe electrode and the counter electrode, and repeating sequentially the pulses of electric voltage and ultrasonic signal until the desired amount of molybdenum sulphide IF structures is deposited; and
- (e) recovering the thus precipitated molybdenum sulphide IF structures.

#### BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1. Transmission electron microscopy (TEM) image of the sonoelectrochemically-prepared MoS<sub>2</sub> powder. The inset in the top lefthand corner shows part of the image at x 2 magnification.

Fig. 2. TEM images of the same MoS<sub>2</sub> particle taken with the sample rotated in the direction of the electron beam at an angle of A +45°; B 0°; C -45°.

Fig. 3. TEM image of part of a MoS<sub>2</sub> nanotube.

Fig. 4. TEM image of a large MoS<sub>2</sub> polyhedral structure filled with MoO<sub>2</sub>. The inset at the top lefthand corner shows part of the image at x 3 magnification.

#### DETAILED DESCRIPTION OF THE INVENTION

The invention will be illustrated by the following non-limiting examples and their figures.

*Experimental:* We used a sonoelectrochemical device similar to the one described by Reisse and co-workers.<sup>[15]</sup> A titanium horn (liquid processor, 20 kHz) acts as both the cathode and the ultrasound emitter. The electroactive part of the sonoelectrode is the planar circular surface at the bottom of the horn. A constant current deposition pulse (160 mAcm<sup>-2</sup>) was immediately followed by a sonic pulse (16 W intensity). The on and off times of both current and sonic pulses were the

same (0.34 s). A spiral made of platinum wire (0.5 mm diameter and 15 cm long) was used as counter electrode, and the intensity - 16 W. The electrolyte (100 ml) was an aqueous solution of 50 mM ammonium tetrathiomolybdate  $[(\text{NH}_4)_2\text{MoS}_4]$  and 1 M sodium sulfate  $[\text{NaSO}_4]$  at a pH of 6.0. The deposition was continued for ca. 90 minutes. At the end of the reaction, the precipitate was centrifuged, washed repeatedly with acetone and dried under vacuum.

A transmission electron microscopy (TEM) image of a sample of this powder is shown in Fig. 1. Although there is considerable variation in the size and shape of the individual particles, they are typically several tens of nm in size and most of the particles have sizes which are the same order of magnitude in all three dimensions. However, there is some variability in the shapes, as can be seen in Fig. 1, where the dimension can be twice as much in one direction as in the others. The crystalline layers (typically between 12 and 15) of  $\text{MoS}_2$  can be clearly seen surrounding a featureless core. From such a two-dimensional picture, we cannot tell if the particles are in the form of discs (or cylinders) or whether they are surrounded by the  $\text{MoS}_2$  layers in all directions like the  $\text{W}(\text{Mo})\text{S}_2$  fullerene-like structures.

Fig. 2 displays TEM images of the same particle at different orientations to the electron beam. The fact that the molecular layers are seen at different angles is a convincing demonstration of the curved and closed nature of the structures. If the sample were flat, as is normally the case for this material, an image of the layers would be seen only when the layers were aligned with the electron beam. In a closed, curved structure, part of the layers will always be aligned with the beam, regardless of the orientation. By the same argument, the different (002) planes will only be visible when they are approximately parallel to the electron beam, i.e., at the outer portions of the 'spheres'. They will become increasingly less visible toward the center of the structure. Also, if we assume a roughly spherical shape, the particle will be thicker near the center, resulting in less transmission of the electron beam and loss of information. Therefore we cannot state definitively if these structures are made up entirely of  $\text{MoS}_2$  sheets, are hollow or contain a core of

another material ( $\text{MoO}_2$ , amorphous  $\text{MoS}_2$ ). The presence of  $\text{MoS}_2$  planes inside the closed structures, but oriented in various directions, as seen in Fig. 2 (and particularly clearly in Fig. 2(c)) suggests that the structures are hollow to some extent. Some of these planes could lie on the outer surface of the structures; however the observation that they almost always terminate within the boundaries of the closed structures suggest that this is less likely.

Occasionally seen, are nanotubes, with the long axis much larger than the cross section (Fig. 3 shows part of one of these nanotubes). Also sometimes seen are larger ( $>100$  nm), irregularly-shaped polyhedral structures (Fig. 4). The number of  $\text{MoS}_2$  layers in these larger structures is no greater than in the smaller ones and most of the structure is featureless to TEM. However, ED of the structure in Fig. 4 showed the presence of  $\text{MoO}_2$  in addition to  $\text{MoS}_2$ . X-ray diffraction (not shown) confirmed the presence of  $\text{MoO}_2$  (monoclinic, powder pattern 32-671). In addition the (002) reflection of the  $\text{MoS}_2$  was shifted slightly to lower angles. The shift to smaller angles compared with normal  $\text{MoS}_2$  can be explained either by strain-induced lattice expansion characteristic of closed  $\text{Mo}(\text{W})\text{S}_2$  structures [4,18] or to the presence of oxygen as  $\text{MoO}_x\text{S}_2$ .<sup>[19]</sup>

Recently, the sonochemical synthesis of  $\text{MoS}_2$  has been reported by Mdlelini et al.<sup>[20]</sup> In this work,  $\text{Mo}(\text{CO})_6$  and elemental sulphur in tetramethylbenzene were subjected to high intensity ultrasonic radiation. The initially formed  $\text{MoS}_2$ , which was amorphous, was crystallized by heating at  $450^\circ\text{C}$  for 10 hr to give a layered, nanostructured product. In order to check if our  $\text{MoS}_2$  could also be formed in the absence of an electrochemical process, our electrodeposition solution was subjected to ultrasonic radiation (16 W continuous radiation for 90 min). A brown-black powder was formed in the solution. This powder was completely diffraction amorphous (no XRD or electron diffraction pattern could be discerned, even at a very slow XRD scan rate of  $0.15^\circ/\text{mn}$ ). On heating to  $400^\circ\text{C}$ , a mixture of  $\text{MoS}_2$  and various phases of  $\text{MoO}_3$  were found by XRD. Therefore, the combination of both electrochemical and ultrasonic processes was necessary to form the crystallized and closed  $\text{MoS}_2$  structures from the solution used by us. We note that Mdlelini et al.

obtained curved nanostructures in their annealed samples (seen from the TEM micrograph in fig. 2 of their paper). It is possible that their structures are also closed - either partially or completely: however, in the absence of angle-dependent micrographs, this cannot be determined from their paper.

We suggest the following mechanism to explain formation of the closed curved structures. Amorphous MoS<sub>2</sub> is formed by electrodeposition onto the sonic probe cathode. The subsequent sonic shock wave then removes this deposit from the probe surface. The deposit could be spheroidal (nucleating electrodeposits are often nanoparticulate) or planar (crystalline MoS<sub>2</sub> would probably form as sheets, but the amorphous material is less likely to do so). At this point, it is conceivable that the effect of this shock wave is itself sufficient to crystallize the deposit. More probable, however, is that the cause of the crystallization, and possibly bending, which normally require high temperatures, is the collapse of the cavitation bubbles.

Electrodeposition or ultrasonic irradiation alone result in X-ray amorphous Mo-S products, but the combination of both gives well-crystallized closed structures of MoS<sub>2</sub>. This technique allows room temperature preparation of large amounts of closed MoS<sub>2</sub> nanoclusters. Ultrasonic radiation is as useful for inducing physical reactions (in this case, crystallization and shaping) as it is for chemical reactions. The combination of electrochemical and sonic processes provide many experimental variables which allow control of particle size, shape, and size and shape distribution and will probably be applicable to the formation of closed structures of other layered compounds which can be prepared by electrochemical (and quite likely also chemical) techniques.

## References

- [1] H.W. Kroto, J.R. Heath, S.C. O'Brien, R.F. Curl and R.E. Smalley, *Nature*, 1985, 318, 162.
- [2] S. Iijima, *J. Crystal. Growth*, 1980, 50, 675.
- [3] R. Tenne, L. Margulis, M. Genut and G. Hodes, *Nature*, 1992, 360, 444.
- [4] Y. Feldman, E. Wasserman, D.J. Srolovitz and R. Tenne, *Science*, 1995, 267, 222.
- [5] Y. Rosenfeld Hacohen, E. Grunbaum, R. Tenne, J. Sloan and J.L. Hutchison, *Nature*, 1998, 395, 336.
- [6] S. Iijima, *Nature*, 1991, 354, 56.
- [7] O. Stephane, P.M. Ajayan, C. Colliex, Ph. Redlich, J.M. Lambert, P. Bernier and P. Lefin, *Science*, 1994, 266, 1683.
- [8] M.E. Spahr, P. Bitterli, R. Nesper, M. Müller, F. Krumeich and H.U. Nissen, *Angew. Chem. Int. Ed.*, 1998, 110, 1339.
- [9] W.A. Krätschmer, L.D. Lamb, K. Fostiropoulos and D.R. Huffman, *Nature*, 1990, 347, 354.
- [10] M. Hershfinkel, L.A. Gheber, V. Volterra, J.L. Hutchinson, L. Margulis and R. Tenne, *J. Am. Chem. Soc.*, 1994, 116, 1914.
- [11] L.T. Chadderton, D. Fink, Y. Gamaly, H. Moeckel, L. Wang, H. Omichi and F. Hosoi, *Nucl. Instrum. Methods Phys. Res.*, 1994, B91, 71.
- [12] M. Homyonfer, Y. Mastai, M. Hershfinkel, V. Volterra, J.L. Hutchinson and R. Tenne, *J. Am. Chem. Soc.*, 1996, 118, 7804.

---

- [13] a) K.S. Suslick, S.-B. Choe, A.A. Cichovlas and M.W. Grinstaff. *Nature* 1991, 353, 414. b) K.S. Suslick, *Ultrasound: Its Chemical, Physical and Biological Effects*, Eds. VCH, Weinheim, 1988.
- [14] a) T.J. Mason, J.P. Walton and D.J. Lorimer, *Ultrasonics*, 1990, 28, 333.  
b) T.J. Mason, J.P. Walton and D.J. Lorimer, *Ultrasonics*, 1990, 28, 251.  
c) T.J. Mason, *Practical Sonoelectrochemistry*, Ellis Horwood, Chichester, 1991.

- [15] A.Durant, J.L. Deplancke, R.Winand and J.Reisse, *Tetrahedron Lett.*, **1995**, 36, 4257.
- [16] H.J. Byker and A.E. Austin, *J. Electrochem. Soc.*, **1981**, 128, 381C (abstract no. 536).
- [17] E.A. Ponomarev, M. Neumann-Spallart, G. Hodes and C. Levy-Clement, *Thin Solid Films*, **1996**, 280, 86.
- [18] Y. Feldman, G.L. Frey, M. Homyonfer, V. Lyakhovitskaya, L. Margulis, H. Cohen, G. Hodes, J.L. Hutchison and R. Tenne, *J. Am. Chem. Soc.*, **1996**, 118, 5362.
- [19] V. Buck, *Thin Solid Films*, **1991**, 198, 157 (1991); E. Schmidt, F. Weill, G. Meunier and A. Levasseur, *Thin Solid Films*, **1994**, 245, 34.
- [20] M.M. Mdleleni, T. Hyeon and K.S. Suslick, *J. Am. Chem. Soc.*, **1998**, 120, 6189.

CLAIMS:

1. A method for the sonoelectrochemical liquid-phase synthesis of inorganic fullerene-like (hereinafter IF) structures of metal chalcogenides , wherein said metal is selected from In, Ga, Sn and a transition metal selected from Mo, W, V, Zr, Hf, Pt, Re, Nb, Ta, Ti, Cr and Ru., and the chalcogen is S, Se or Te, the method comprising the steps of:

(a) dissolving in a suitable solvent: (a) at least one compound of said metal and at least one compound of said chalcogen, or (b) at least one said chalcogen-containing said metal compound;

(b) immersing an electrically conductive ultrasonic probe in the solution obtained in (a);

(c) electrically connecting the ultrasonic probe, which operates as an electrode, to one terminal of an electric power supply, and the other terminal of said electric power supply is connected to a counter electrode;

(d) applying an ultrasonic signal to said ultrasonic probe electrode and an electric voltage to both the ultrasonic probe electrode and the counter electrode: and

(e) recovering the IF-metal chalcogenide structures that precipitated in (d).

2. The method according to claim 1 wherein said suitable solvent in step (a) is aqueous or non-aqueous.

3. The method according to claim 1 or 2, wherein the synthesis is carried out at a temperature in which said solvent is in the liquid state.

4. The method according to claim 3, wherein said solvent is water and the synthesis is carried out at room temperature.

5. The method according to any one of claims 1 to 4, wherein said ultrasonic probe is Ti.

6. The method according to any one of claims 1 to 5, which comprises applying in step (d) first an electric voltage to both the ultrasonic probe electrode and the counter electrode which is then followed by an ultrasonic signal to the ultrasonic probe electrode, and repeating the sequences of electric voltage and ultrasonic signal until the desired amount of IF-metal chalcogenide structures is obtained.

7. The method according to claim 6, wherein the ultrasonic probe electrode is connected to the negative terminal of the electric power supply and the counter electrode to the positive terminal.

8. The method according to any one of claims 1 to 7, wherein the metal is a transition metal selected from Mo, W, V, Zr, Hf, Pt, Re, Nb, Ta, Ti, Cr and Ru.

9. The method according to claim 8, wherein said metal is Mo.

10. A method for the sonoelectrochemical liquid phase synthesis of inorganic fullerene-like (hereinafter IF) structures of molybdenum sulphide, comprising the steps of:

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(a) dissolving in a suitable solvent: (a) at least one molybdenum compound with at least one sulphur compound, or (b) a sulphur-containing molybdenum compound;

(b) immersing an electrically conductive ultrasonic probe in the solution obtained in (a);

(c) electrically connecting the ultrasonic probe, which operates as an electrode, to one terminal of an electric power supply, and the other terminal of said electric power supply is connected to a counter electrode;

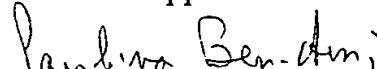
(d) applying an ultrasonic signal to said ultrasonic probe electrode and an electric voltage to both the ultrasonic probe electrode and the counter electrode; and

(e) recovering the molybdenum sulphide IF structures that precipitated in (d).

11. A method according to claim 10 for room temperature sonoelectrochemical synthesis of inorganic fullerene-like (hereinafter IF) structures of molybdenum sulphide, comprising the steps of:

- (a) dissolving ammonium tetrathiomolybdate in water;
- (b) immersing an electrically conductive ultrasonic Ti probe in the solution obtained in (a);
- (c) electrically connecting the ultrasonic probe, which operates as an electrode, to one terminal of an electric power supply, and the other terminal of said electric power supply is connected to a counter electrode;
- (d) applying an ultrasonic signal to said ultrasonic probe electrode and an electric voltage to both the ultrasonic probe electrode and the counter electrode, and repeating sequentially the pulses of electric voltage and ultrasonic signal until the desired amount of molybdenum sulphide IF structures is deposited; and
- (e) recovering the thus precipitated molybdenum sulphide IF structures.

For the Applicants



Paulina Ben-Ami

Patent Attorney

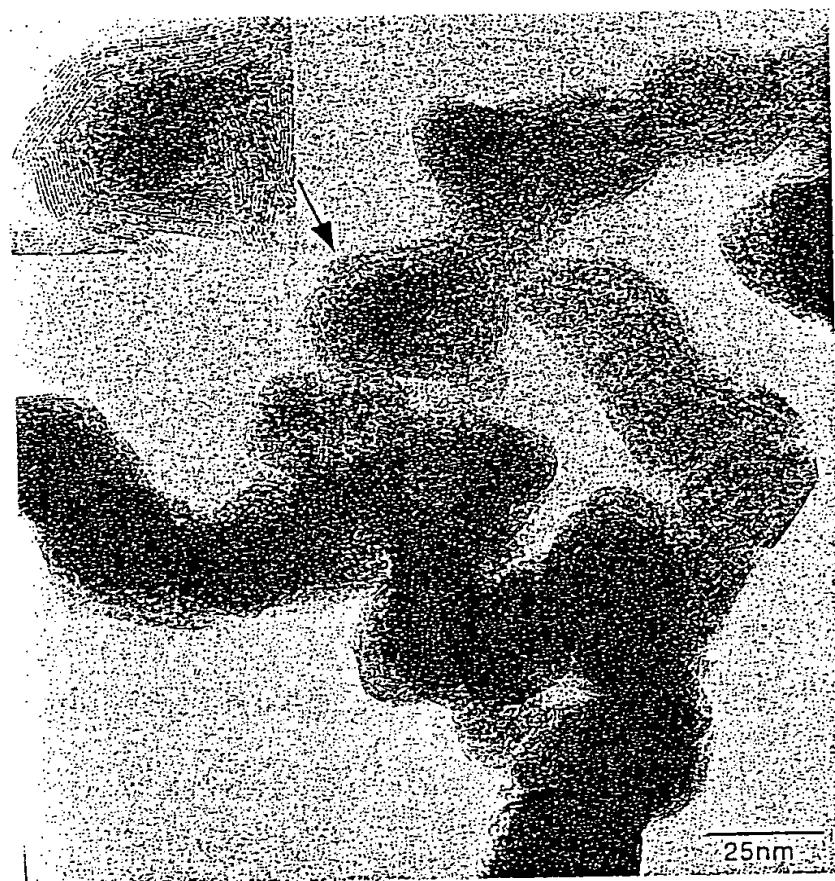


Fig. 1

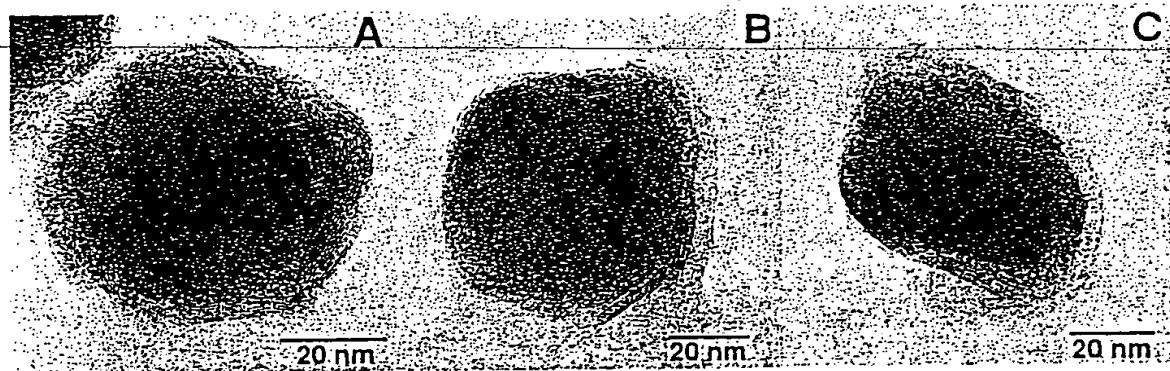


Fig. 2



Fig. 3

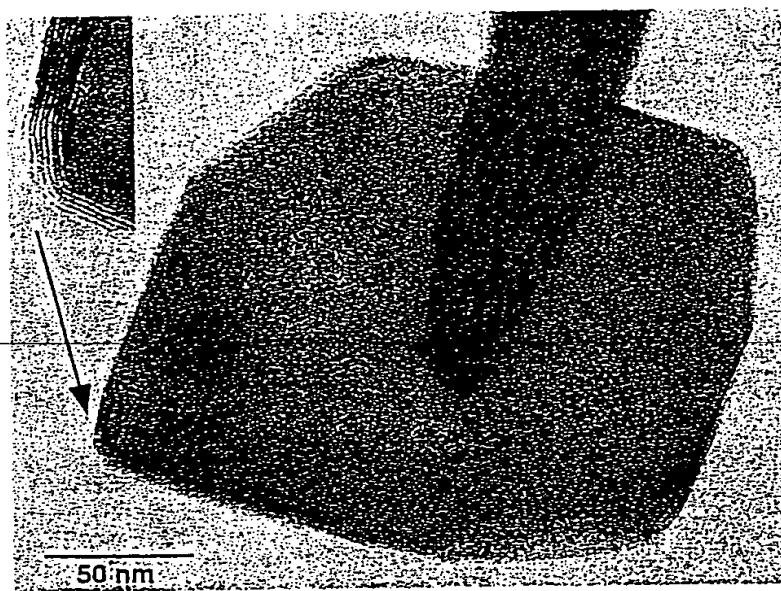


Fig. 4